Teesside University

Techno-Economic Analysis of Li-ion Batteries in the Capacity Market with Different Degradation Models

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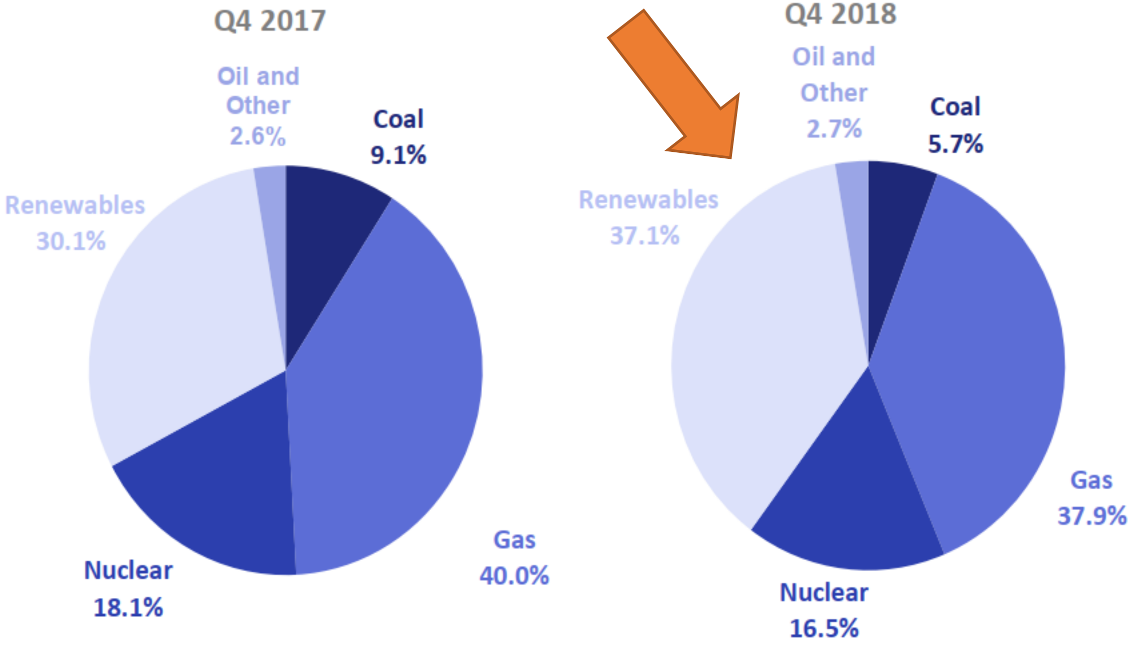
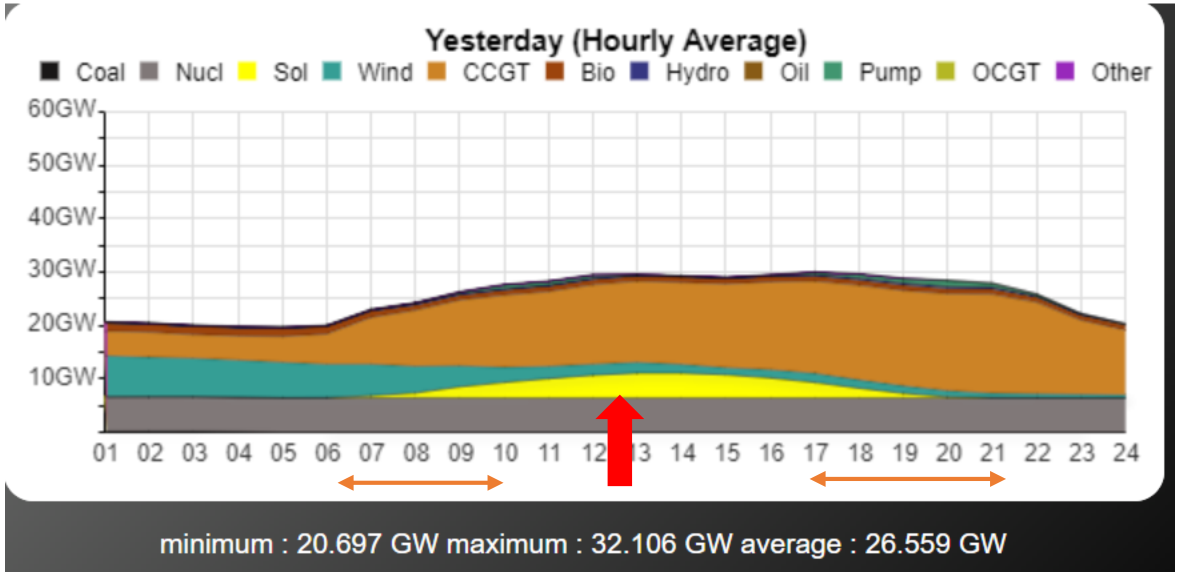
05/09/2019

Introduction



Source: BEIS, Energy trends, 2019



Source: UK Grid watch, 2019

Energy-only markets

- Energy-only market **only compensates generated MW that is actually produced**
- Capacity is only indirectly compensated based on implicit supply agreements, such as futures contracts
- The question is what happens with the prices for imbalances when there is a loss of load occasion (LOLO). If there is a LOLO (i.e., demand larger than available capacity), then this means that there is at least one trader/retailer who sells power without having that power to sell.

Energy-only markets

The Guardian

UK ▸ UK politics Education Media Society Law Scotland **Wales** Northern Ireland

National Grid

UK energy watchdog demands answers after major power cut

Outage caused travel chaos and cut electricity to almost 1m people in England and Wales

INDEPENDENT

UK power cut: What happened, why it was so bad and who is to blame for outage that left 1 million in the dark?

Incident a 'wake-up call' to energy industry

London experienced rush-hour chaos today when the power died across the country

Source: Telegraph

Energy

How batteries stopped the UK's power cut being a total disaster

On Friday afternoon, Britain's power grid fell apart when two power plants went offline. But a handful of battery firms prevented things from getting much worse

BBC NEWS

UK power cut: Andrea Leadsom launches government investigation

11 August 2019

Share

UK power cut

Energy-only market failure

If there is a blackout,

The duration of the blackout depends on the generation capacity built to avoid them

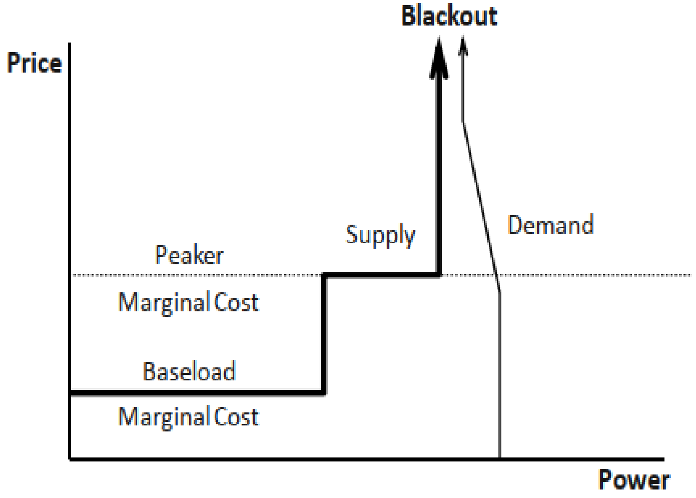
The incentive to build new generation capacity depends on the price being paid during blackouts (scarcity prices)

this would result in the price rising without limit since demand is very **inelastic**

because customers are unaware of the real-time price of electricity or have no reason to respond to them

Since this is not desirable, the energy price is capped low.

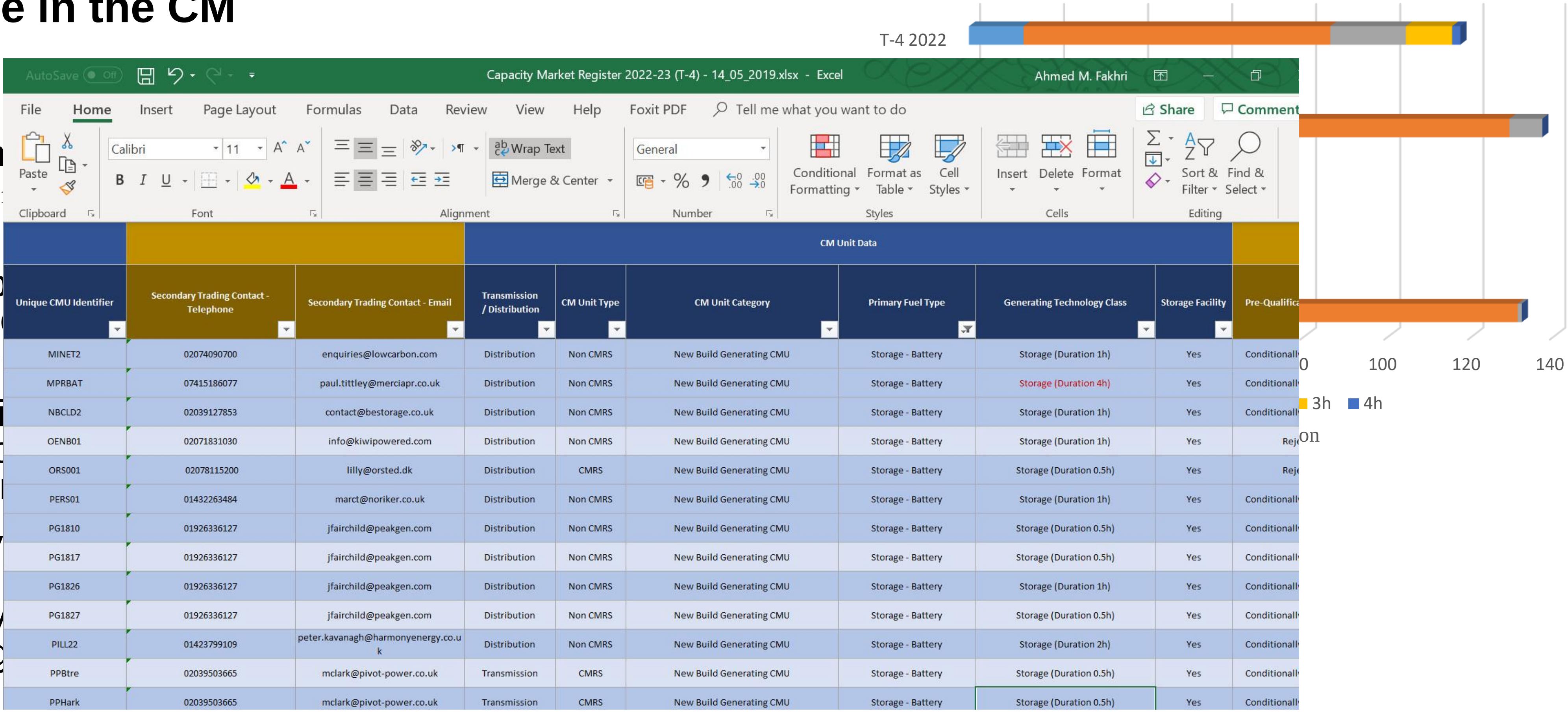
That means there is "missing money," which implies there is low a level of investment in capacity.



Source: Capacity market fundamentals, Cramton et.al,2013

Energy Storage in the CM

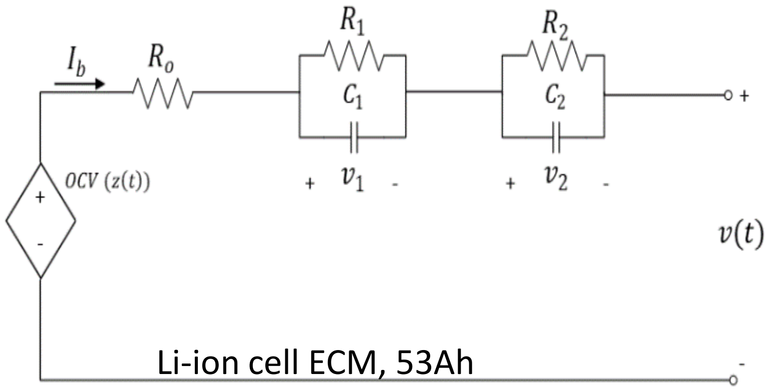
- Batteries can p
traditional gen
investment in n
plant (S. Forrester, et al. 201
- It is found that
case by particip
of reducing th
reducing the sh
- Most of the revi
CM at all, or co
modelling batte
- Energy delivery
time during the
remain in a fully
able to discharg
occur (Gissey et.al, 2018)



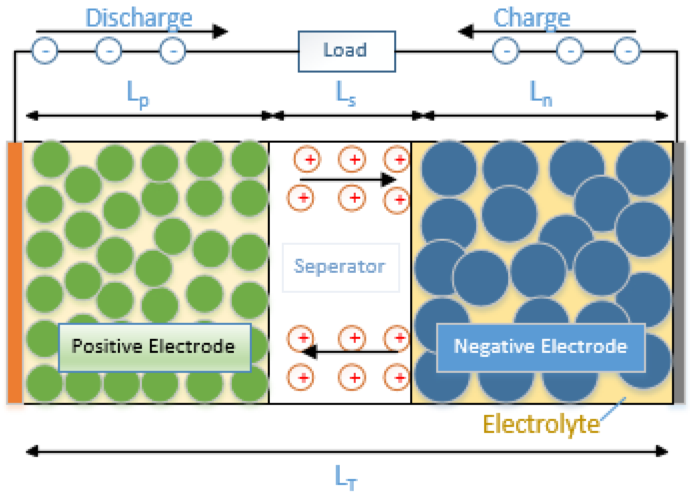
			CM Unit Data						
Unique CMU Identifier	Secondary Trading Contact - Telephone	Secondary Trading Contact - Email	Transmission / Distribution	CM Unit Type	CM Unit Category	Primary Fuel Type	Generating Technology Class	Storage Facility	Pre-Qualifica
MINET2	02074090700	enquiries@lowcarbon.com	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 1h)	Yes	Conditionall
MPRBAT	07415186077	paul.tittley@merciapr.co.uk	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 4h)	Yes	Conditionall
NBCLD2	02039127853	contact@bestorage.co.uk	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 1h)	Yes	Conditionall
OENB01	02071831030	info@kiwipowered.com	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 1h)	Yes	Rej
ORS001	02078115200	lilly@orsted.dk	Distribution	CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 0.5h)	Yes	Reje
PERS01	01432263484	marct@noriker.co.uk	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 1h)	Yes	Conditionall
PG1810	01926336127	jfairchild@peakgen.com	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 0.5h)	Yes	Conditionall
PG1817	01926336127	jfairchild@peakgen.com	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 0.5h)	Yes	Conditionall
PG1826	01926336127	jfairchild@peakgen.com	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 1h)	Yes	Conditionall
PG1827	01926336127	jfairchild@peakgen.com	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 0.5h)	Yes	Conditionall
PILL22	01423799109	peter.kavanagh@harmonyenergy.co.uk	Distribution	Non CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 2h)	Yes	Conditionall
PPBtre	02039503665	mclark@pivot-power.co.uk	Transmission	CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 0.5h)	Yes	Conditionall
PPHark	02039503665	mclark@pivot-power.co.uk	Transmission	CMRS	New Build Generating CMU	Storage - Battery	Storage (Duration 0.5h)	Yes	Conditionall

Methods

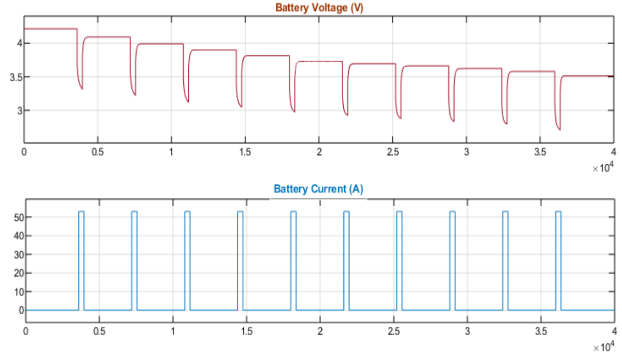
1- Battery models:

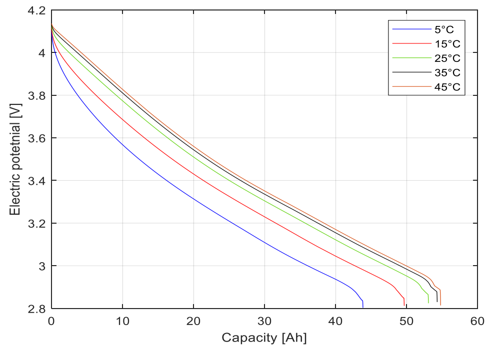


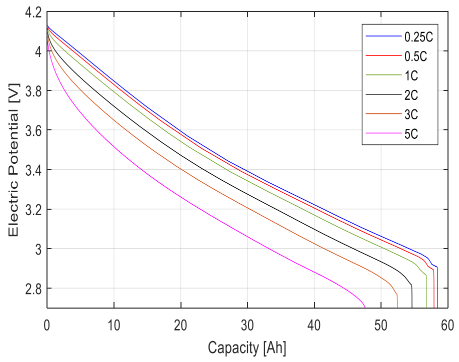
Li-ion cell ECM, 53Ah



Battery
Cn = 53Ah, Vn = 3.7V
String: 12 cells in series, 3.7*12 = 44.4V @53Ah
Module: 4 strings in parallel, 4*53=212Ah @44.4V
Rack = 14 modules in series, 15*44.4 = 666V @212Ah
Battery = 15 rack in parallel, 14*212=2968Ah @666V
Total: 2968*666 ≈2 MWh
Number of cells (N) ≈ 10080



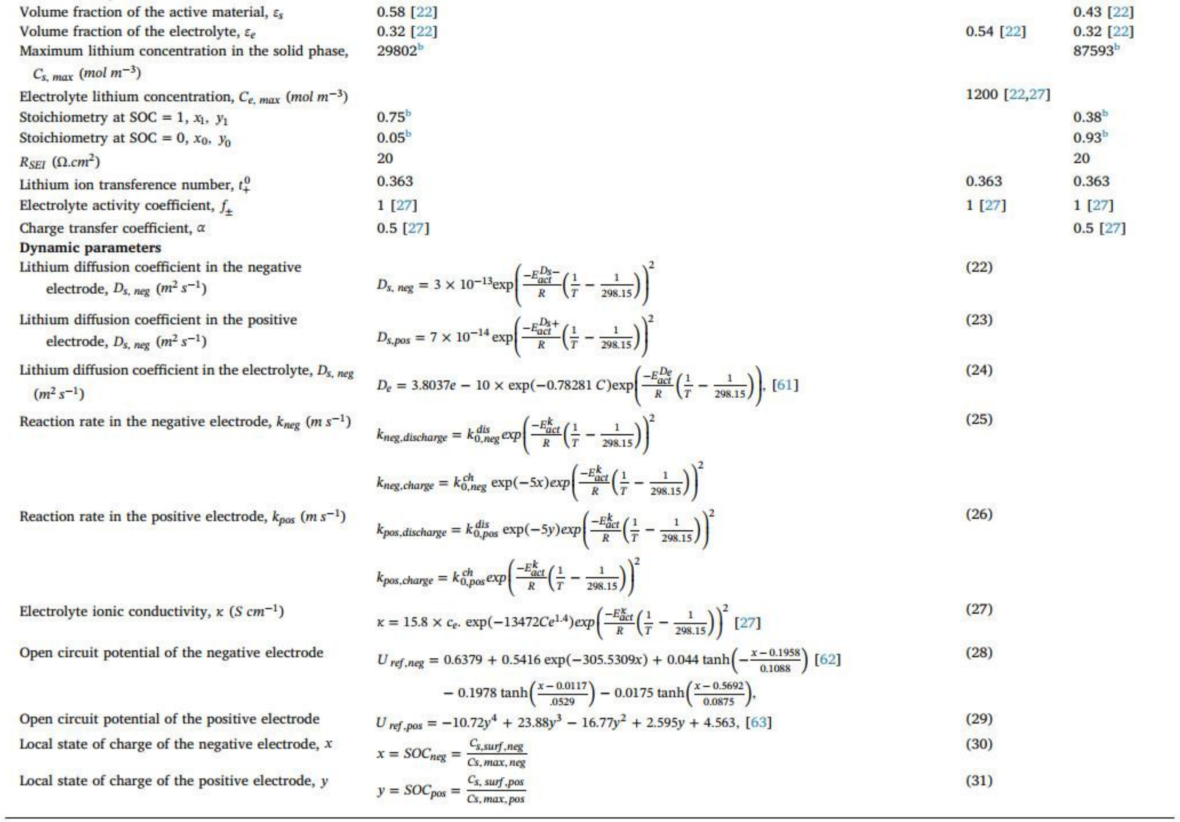




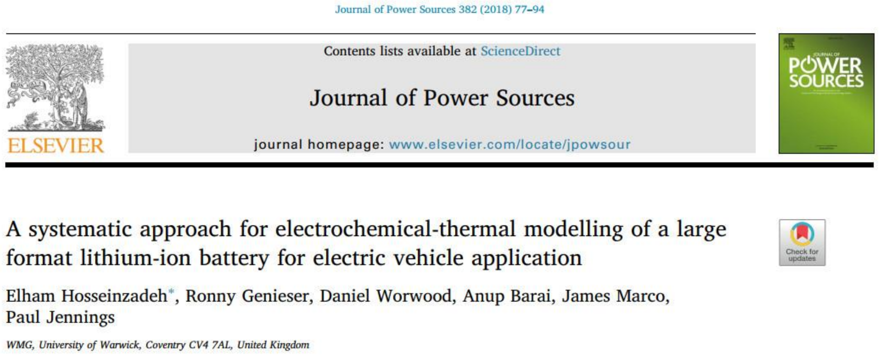
COMSOL

Methods

1- Battery models:



Volume fraction of the active material, ε_s	0.58 [22]		0.43 [22]
Volume fraction of the electrolyte, ε_e	0.32 [22]	0.54 [22]	0.32 [22]
Maximum lithium concentration in the solid phase, $C_{s,\,max}$ $(mol\ m^{-3})$	29802^{b}		87593^{b}
Electrolyte lithium concentration, $C_{e,\,max}$ $(mol\ m^{-3})$		1200 [22,27]	
Stoichiometry at SOC = 1, x_1, y_1	0.75^{b}		0.38^{b}
Stoichiometry at SOC = 0, x_0, y_0	0.05^{b}		0.93^{b}
R_{SEI} $(\Omega.cm^2)$	20		20
Lithium ion transference number, t_+^0	0.363	0.363	0.363
Electrolyte activity coefficient, $f_\pm$	1 [27]	1 [27]	1 [27]
Charge transfer coefficient, α	0.5 [27]		0.5 [27]
Dynamic parameters			
Lithium diffusion coefficient in the negative electrode, $D_{s,\,neg}$ $(m^2\ s^{-1})$	$D_{s,\,neg} = 3\times10^{-13}\exp\left(\frac{-E_{act}^{Ds-}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$	(22)	
Lithium diffusion coefficient in the positive electrode, $D_{s,\,neg}$ $(m^2\ s^{-1})$	$D_{s,pos} = 7\times10^{-14}\exp\left(\frac{-E_{act}^{Ds+}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$	(23)	
Lithium diffusion coefficient in the electrolyte, $D_{s,\,neg}$ $(m^2\ s^{-1})$	$D_e = 3.8037e-10\times\exp(-0.78281\ C)\exp\left(\frac{-E_{act}^{De}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)$, [61]	(24)	
Reaction rate in the negative electrode, k_{neg} $(m\ s^{-1})$	$k_{neg,discharge} = k_{0,neg}^{dis}\exp\left(\frac{-E_{act}^{k}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$ $k_{neg,charge} = k_{0,neg}^{ch}\exp(-5x)\exp\left(\frac{-E_{act}^{k}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$	(25)	
Reaction rate in the positive electrode, k_{pos} $(m\ s^{-1})$	$k_{pos,discharge} = k_{0,pos}^{dis}\exp(-5y)\exp\left(\frac{-E_{act}^{k}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$ $k_{pos,charge} = k_{0,pos}^{ch}\exp\left(\frac{-E_{act}^{k}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$	(26)	
Electrolyte ionic conductivity, κ $(S\ cm^{-1})$	$\kappa = 15.8\times c_e.\ \exp(-13472Ce^{1.4})\exp\left(\frac{-E_{act}^{k}}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right)^2$ [27]	(27)	
Open circuit potential of the negative electrode	$U_{ref,neg} = 0.6379 + 0.5416\exp(-305.5309x) + 0.044\tanh\left(-\frac{x-0.1958}{0.1088}\right)$ [62] $-0.1978\tanh\left(\frac{x-0.0117}{.0529}\right) - 0.0175\tanh\left(\frac{x-0.5692}{0.0875}\right)$,	(28)	
Open circuit potential of the positive electrode	$U_{ref,pos} = -10.72y^4 + 23.88y^3 - 16.77y^2 + 2.595y + 4.563$, [63]	(29)	
Local state of charge of the negative electrode, x	$x = SOC_{neg} = \frac{C_{s,surf,neg}}{C_{s,max,neg}}$	(30)	
Local state of charge of the positive electrode, y	$y = SOC_{pos} = \frac{C_{s,surf,pos}}{C_{s,max,pos}}$	(31)	



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journal homepage: www.elsevier.com/locate/jpowsour

A systematic approach for electrochemical-thermal modelling of a large format lithium-ion battery for electric vehicle application

Elham Hosseinzadeh*, Ronny Genieser, Daniel Worwood, Anup Barai, James Marco, Paul Jennings

WMG, University of Warwick, Coventry CV4 7AL, United Kingdom

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2- Battery degradation models

A-Empirical (E) by Schmalstieg et.al

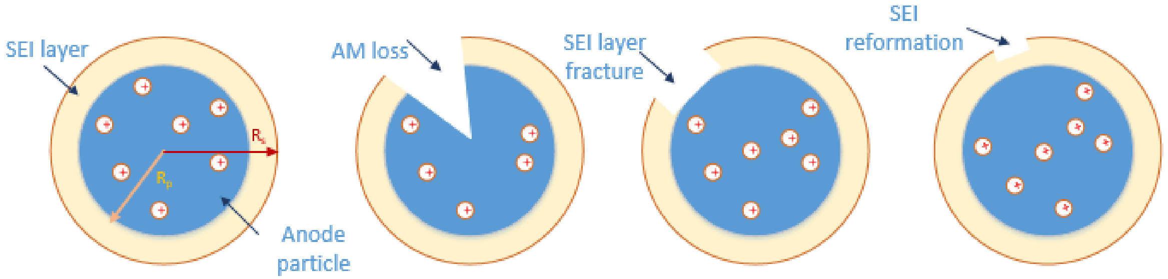
$$C_{lost1} = \left(\alpha(V_{av},T)t^{0.75} + \beta(DoD,V_{av}) \times 2DoD\,N_c C_n \int I(t)\,dt\right)$$

B-Semi-Empirical (S) by NREL

$$C_{lost2} = min\left(Q_{li}(t,T,N_c,DoD,V_{oc}(t)), Q_{neg}(T,DoD,N_c), Q_{pos}(DoD)\right)$$

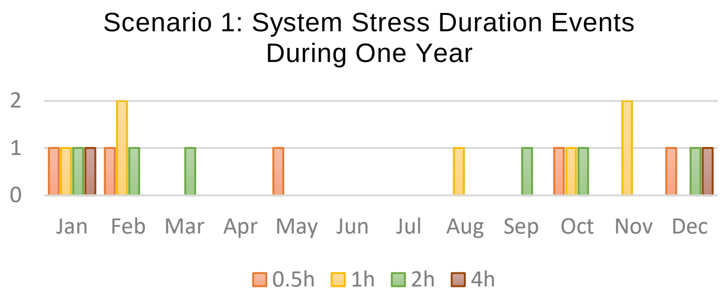
C-Physics (P) by Jin and Liu

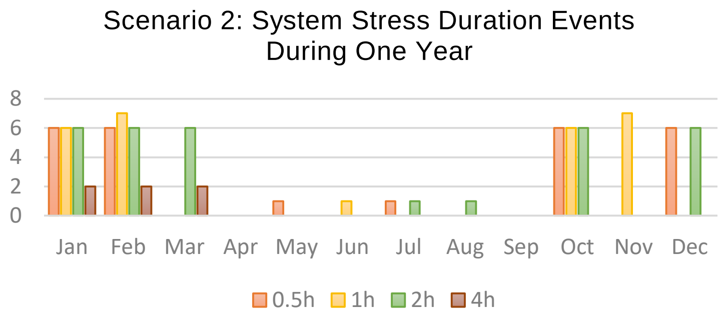
$$C_{lost3} = \sum\left(\int_0^t i_s(t)\,dt + \int_0^t SoC\,d\varepsilon_{AM} + \sum_{i=1}^{Nc} Q_{SEI,crack}\right)$$



3- CM regulations and scenarios

Battery Capacity	Connection Capacity	De-rated capacity	Hours
2 MWh	2 MW	0.43 MW	0.5
2 MWh	2 MW	0.81 MW	1
2 MWh	1 MW	0.68 MW	2
2 MWh	0.5 MW	0.48 MW	4


Scenario 1: System Stress Duration Events During One Year


Scenario 2: System Stress Duration Events During One Year

The Revenue (R) of the battery in the CM is calculated as:

$$R = C_{de}\,\lambda_{cl}\,f + R_{ov} - p$$

Where

$C_{de} = P_c\,k_{de}$,

$P_c = I_b\,V_b N$,

$p = \sum_{i=1}^{n} C_{un(i)}\frac{\lambda_{cl}}{24}$,

$R_{ov} = C_{ov(i)}\,\min(\lambda, \frac{p_T}{C_{ovT}})$

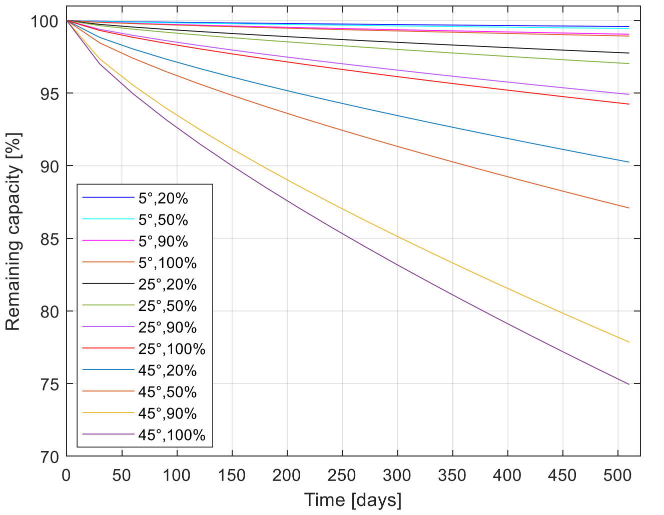
The degradation cost is

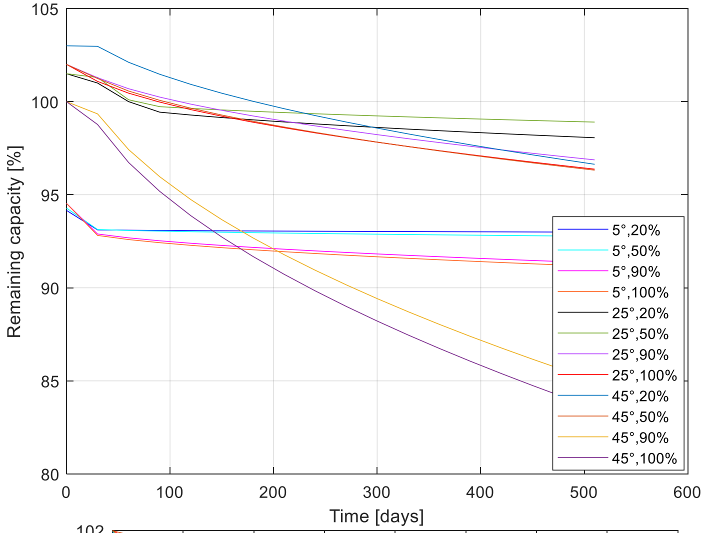
$$E_{lost} = C_{lost}\;\lambda_{degr}\;N$$

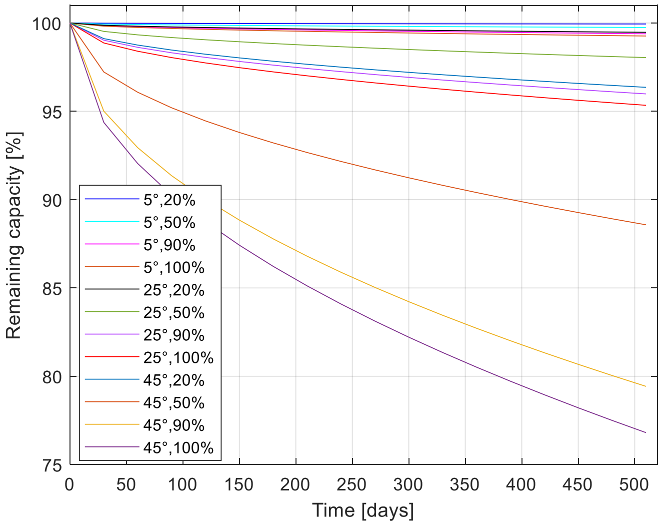
The capacity obligation (C_o) during stress event is calculated:

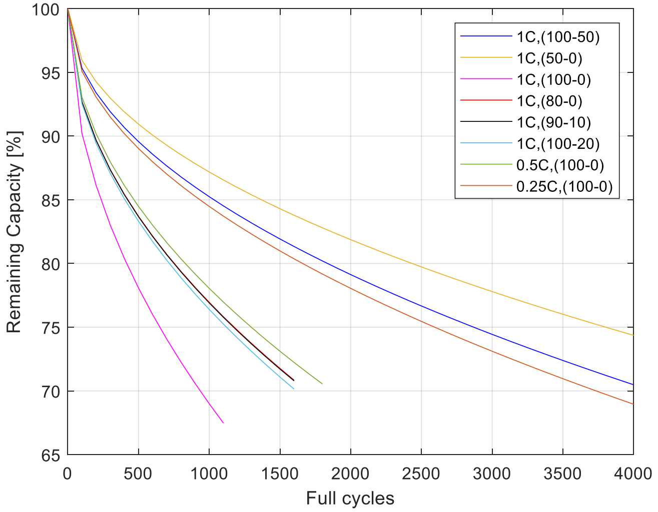
$$C_o = \sum_{i=1}^{n}\left(C_{de}D_p(i)\right) - C_b(i),\;\; D_p = \frac{D_p^{sse}}{C_{ac}}$$

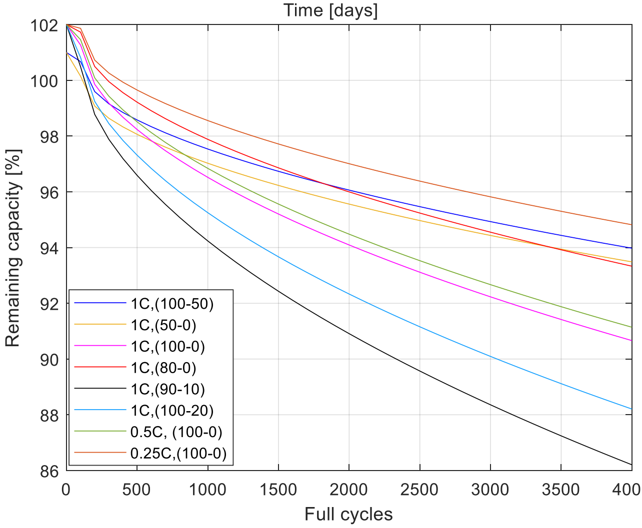
Results

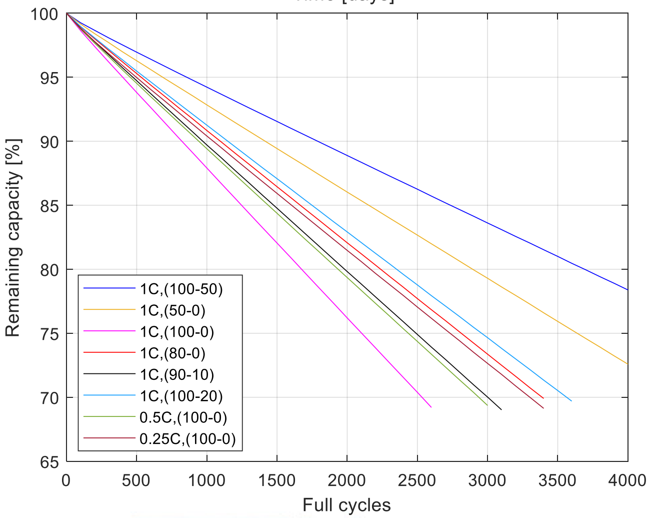

Remaining capacity [%]
100
95
90
85
80
75
70
0
50
100
150
200
250
300
350
400
450
500
Time [days]
5°,20%
5°,50%
5°,90%
5°,100%
25°,20%
25°,50%
25°,90%
25°,100%
45°,20%
45°,50%
45°,90%
45°,100%


Remaining capacity [%]
105
100
95
90
85
80
0
100
200
300
400
500
600
Time [days]
5°,20%
5°,50%
5°,90%
5°,100%
25°,20%
25°,50%
25°,90%
25°,100%
45°,20%
45°,50%
45°,90%
45°,100%

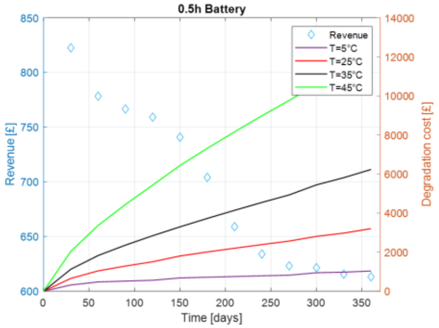

Remaining capacity [%]
100
95
90
85
80
75
0
50
100
150
200
250
300
350
400
450
500
Time [days]
5°,20%
5°,50%
5°,90%
5°,100%
25°,20%
25°,50%
25°,90%
25°,100%
45°,20%
45°,50%
45°,90%
45°,100%

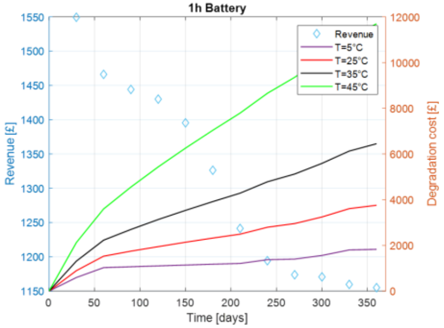

Remaining Capacity [%]
100
95
90
85
80
75
70
65
0
500
1000
1500
2000
2500
3000
3500
4000
Full cycles
1C,(100-50)
1C,(50-0)
1C,(100-0)
1C,(80-0)
1C,(90-10)
1C,(100-20)
0.5C,(100-0)
0.25C,(100-0)

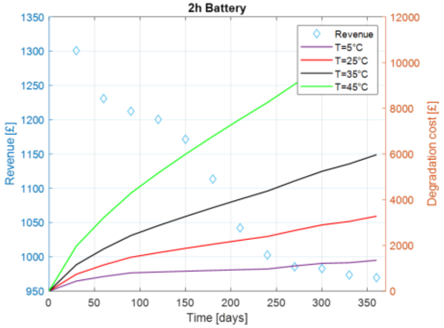

Remaining capacity [%]
102
100
98
96
94
92
90
88
86
0
500
1000
1500
2000
2500
3000
3500
4000
Full cycles
1C,(100-50)
1C,(50-0)
1C,(100-0)
1C,(80-0)
1C,(90-10)
1C,(100-20)
0.5C, (100-0)
0.25C,(100-0)

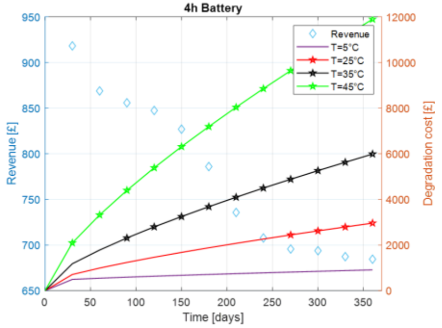

Remaining capacity [%]
100
95
90
85
80
75
70
65
0
500
1000
1500
2000
2500
3000
3500
4000
Full cycles
1C,(100-50)
1C,(50-0)
1C,(100-0)
1C,(80-0)
1C,(90-10)
1C,(100-20)
0.5C,(100-0)
0.25C,(100-0)

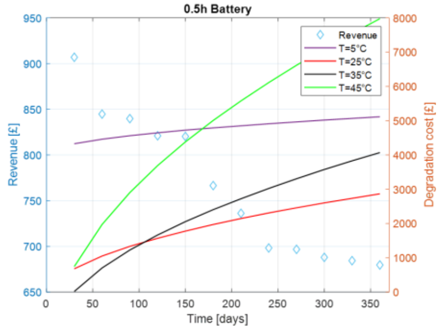
Results

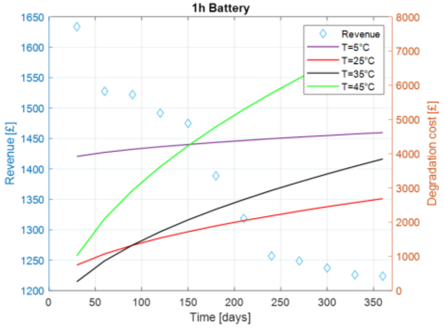

0.5h Battery
Revenue [£]
Degradation cost [£]
Time [days]
850
800
750
700
650
600
14000
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

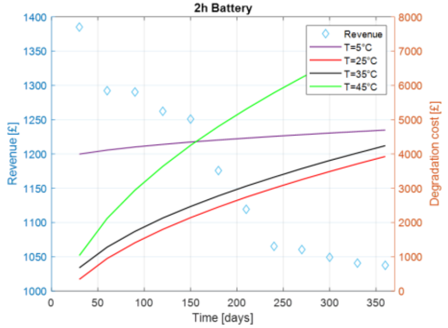

1h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1550
1500
1450
1400
1350
1300
1250
1200
1150
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

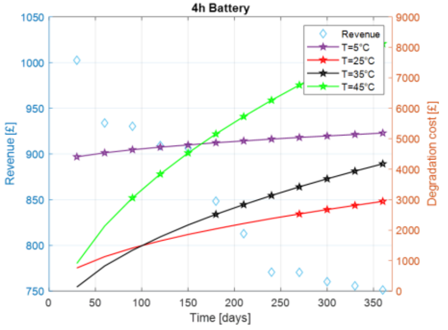

2h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1350
1300
1250
1200
1150
1100
1050
1000
950
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

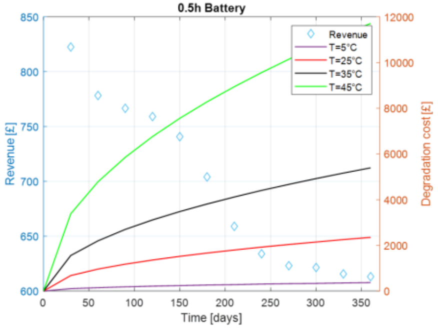

4h Battery
Revenue [£]
Degradation cost [£]
Time [days]
950
900
850
800
750
700
650
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

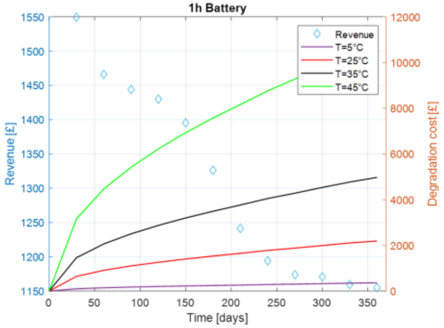

0.5h Battery
Revenue [£]
Degradation cost [£]
Time [days]
950
900
850
800
750
700
650
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

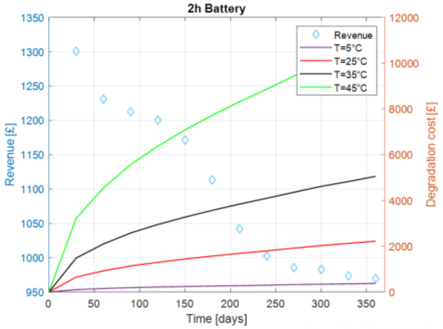

1h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

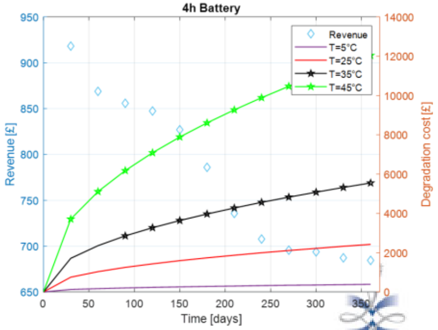

2h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1400
1350
1300
1250
1200
1150
1100
1050
1000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C


4h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1050
1000
950
900
850
800
750
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

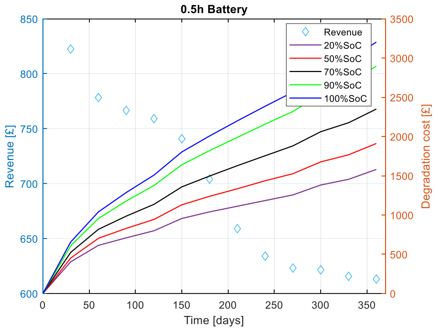

0.5h Battery
Revenue [£]
Degradation cost [£]
Time [days]
850
800
750
700
650
600
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

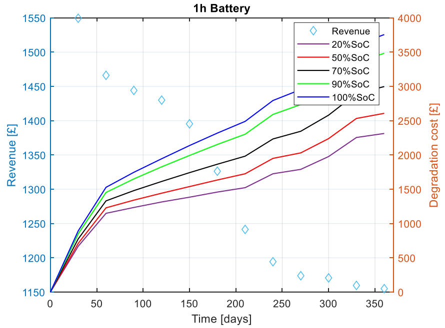

1h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1550
1500
1450
1400
1350
1300
1250
1200
1150
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

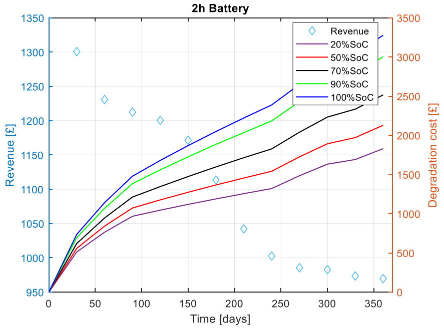

2h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1350
1300
1250
1200
1150
1100
1050
1000
950
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

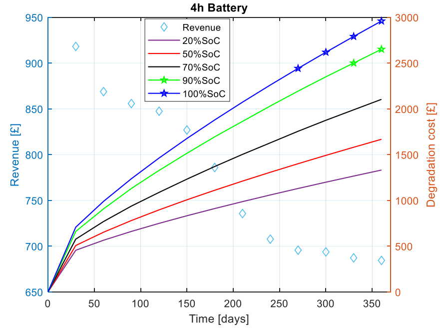

4h Battery
Revenue [£]
Degradation cost [£]
Time [days]
950
900
850
800
750
700
650
14000
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Revenue
T=5°C
T=25°C
T=35°C
T=45°C

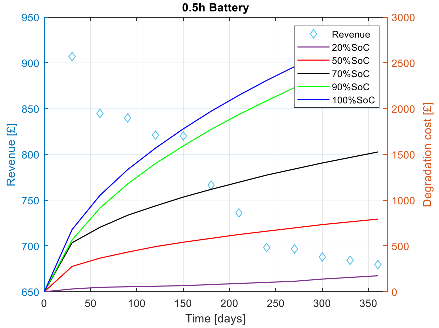
Results

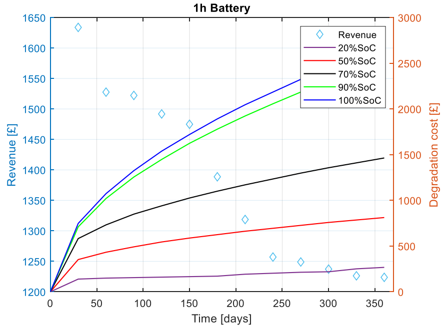

0.5h Battery
Revenue [£]
Degradation cost [£]
Time [days]
600
650
700
750
800
850
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

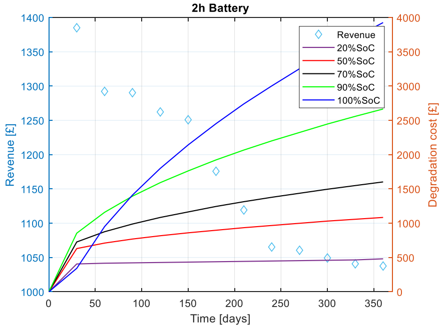

1h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1150
1200
1250
1300
1350
1400
1450
1500
1550
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

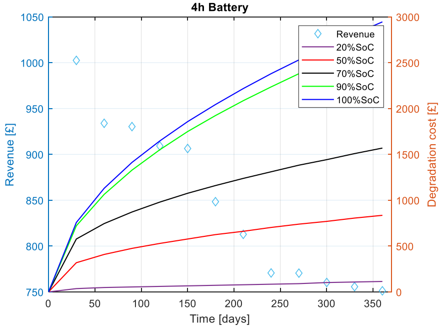

2h Battery
Revenue [£]
Degradation cost [£]
Time [days]
950
1000
1050
1100
1150
1200
1250
1300
1350
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

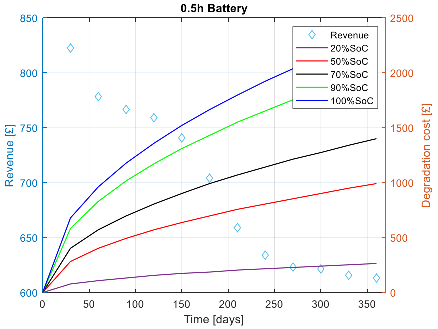

4h Battery
Revenue [£]
Degradation cost [£]
Time [days]
650
700
750
800
850
900
950
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

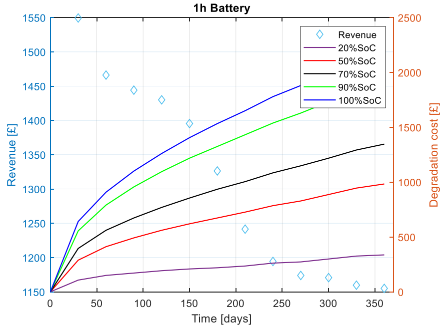

0.5h Battery
Revenue [£]
Degradation cost [£]
Time [days]
650
700
750
800
850
900
950
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

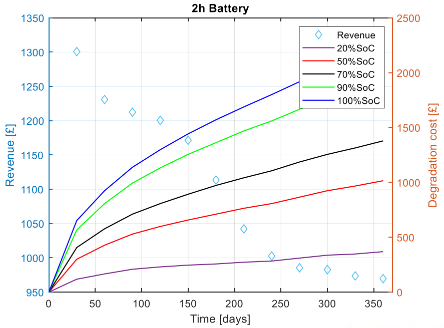

1h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

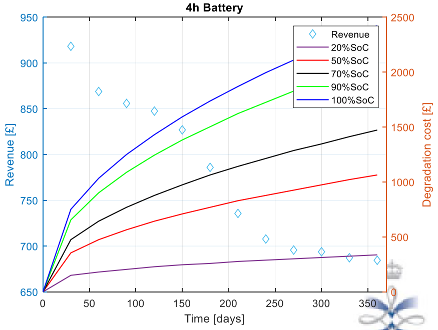

2h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1000
1050
1100
1150
1200
1250
1300
1350
1400
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC


4h Battery
Revenue [£]
Degradation cost [£]
Time [days]
750
800
850
900
950
1000
1050
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC


0.5h Battery
Revenue [£]
Degradation cost [£]
Time [days]
600
650
700
750
800
850
0
500
1000
1500
2000
2500
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC


1h Battery
Revenue [£]
Degradation cost [£]
Time [days]
1150
1200
1250
1300
1350
1400
1450
1500
1550
0
500
1000
1500
2000
2500
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC


2h Battery
Revenue [£]
Degradation cost [£]
Time [days]
950
1000
1050
1100
1150
1200
1250
1300
1350
0
500
1000
1500
2000
2500
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC


4h Battery
Revenue [£]
Degradation cost [£]
Time [days]
650
700
750
800
850
900
950
0
500
1000
1500
2000
2500
0
50
100
150
200
250
300
350
Revenue
20%SoC
50%SoC
70%SoC
90%SoC
100%SoC

Conclusion

- In general, the results illustrate that degradation cost can significantly impact the potential profit from each battery
- The battery with the 1h de-rating factor shows the highest revenue within the current CM regulations
- The empirical degradation model is simple but overestimate the capacity loss especially in the first cycles. It also underestimates the degradation at low temperatures. Keeping the temperature at 5ºC and at low SoC (20%) offers the highest profit
- In contrast, the semi-empirical model shows that the degradation cost is maximum at 5ºC and minimal at 25ºC with SoC(20%). It shows also a slight increase in the revenue for all cases because the battery capacity predicted shows an increase above nominal in the first 50 days of cycling
- The physics model offer a deeper understanding for the complex degradation mechanisms inside the battery but it also underestimate the degradation at low temperatures.
- Although the three models use the same battery chemistry data (NMC), but this does not necessarily means that extrapolation is possible outside the characterisation setup set when collecting the data

Teesside University

Thank you

School of **Science, Engineering & Design**